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Article

Mercury content in the organs of small mammals in different geomorphological regions of the taiga zone of the European part of Russia

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Abstract. The content of total mercury in organs and tissues (brain, muscles, kidneys, and liver) has been studied in common shrew and in common vole, living in different geomorphological regions of the Vologda Oblast. Mercury content is statistically significantly higher (2–5 times) in common shrew than in common vole. In common shrew, average mercury content ($\mu\text{g/g}$ dry weight) decreases in the series: kidneys (0.158 ± 0.016) > liver (0.086 ± 0.01) > muscles (0.084 ± 0.011) > brain (0.059 ± 0.006); in common vole, kidneys (0.026 ± 0.003) > brain (0.024 ± 0.004) > muscles (0.016 ± 0.003) > liver (0.013 ± 0.002). Mercury content in organs of common shrew and of common vole, caught in the western geomorphological region with high swampiness and a large number of lakes, is statistically significantly higher (2–3 times) comparing to those captured in the eastern geomorphological region with a developed river network.

Keywords: common shrew, common vole, food webs, biogenic migration, Vologda Oblast, kidneys, liver, muscles

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Научная статья

Содержание ртути в органах мелких млекопитающих разных геоморфологических областей таежной зоны европейской части России

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Аннотация. Исследовано содержание общей ртути в органах и тканях (мозг, мышцы, почки, печень) обыкновенной бурозубки и обыкновенной полевки, обитающих в разных геоморфологических областях Вологодской области. У обыкновенной бурозубки содержание ртути статистически значимо выше (в 2–5 раз), чем у обыкновенной полевки. У бурозубок средние значения количества ртути (мкг/г сухой массы) уменьшаются в ряду: почки (0.158 ± 0.016) > печень (0.086 ± 0.01) > мышцы (0.084 ± 0.011) > мозг (0.059 ± 0.006); у полевок – почки (0.026 ± 0.003) > мозг (0.024 ± 0.004) > мышцы (0.016 ± 0.003) > печень (0.013 ± 0.002). Содержание ртути в органах бурозубок и полевок, отловленных в западной геоморфологической области с высокой заболоченностью территории и большим количеством озер, статистически значимо в 2–3 раза выше, чем в органах зверьков, отловленных в восточной геоморфологической области с развитой речной сетью.

Ключевые слова: бурозубка, полевка, пищевые сети, биогенная миграция, Вологодская область, почки, печень, мышцы

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Introduction

High toxicity and widespread occurrence of mercury and its compounds in the environment poses a health hazard to most animals. Organomercury compounds are characterized by the high biogeochemical mobility and ability to accumulate in the organs and tissues of living organisms (Covelli et al., 2012; Song et al., 2018; UNEP, 2019).

Numerous studies of aquatic and terrestrial food webs evidence that mercury content tends to increase as the trophic level does, so this element is transferred from aquatic to terrestrial ecosystems (Cristol et al., 2008; Kwon et al., 2015). Abiotic environmental factors predetermine the migration activity of mercury compounds between ecosystem components (Buck et al., 2019; Eagles-Smith et al., 2018; Morel et al., 1998; Ullrich et al., 2001). The mercury accumulation rate in the tissues of living organisms is preconditioned by geographic and climatic environmental factors, while high Hg concentration is not always associated with the presence of anthropogenic sources of mercury (Drenner et al., 2013; Komov et al., 2012; Wiener et al., 2002).

Wetland forest ecosystems play a key role in the global mercury cycle, as their conditions are favorable for methylation and bioaccumulation of mercury (Lu et al., 2016; Obrist, 2007). Waterlogging in the watershed has previously been shown to increase mercury levels in fish (Haines et al., 1992); a similar possible effect of waterlogging on the biota of terrestrial ecosystems has been studied much less. When studying heavy metals in terrestrial ecosystems, small mammals are used as model objects, because they have short lifespans and do not migrate long distances (Al Sayegh Petkovšek et al., 2014; Sanchez-Chardi and López-Fuster, 2009).

The Vologda Oblast, located in the northwest of Russia, may serve as a convenient model platform for studying the influence of natural abiotic factors on the accumulation of mercury by living organisms due to the structural features of the macorelief. Within the region, two large geomorphological regions are distinguished: (1) western one, with a wide distribution of lake basins and many small lakes, and (2) eastern one, with monotonous glacial and glacial-lacustrine landforms (Kichigin, 2007).

The study aims to describe the peculiarities of accumulation and distribution of mercury in the organs and tissues of small mammals of different trophic levels in individual geomorphological regions.

Materials and methods

The Vologda Oblast is located in the northeast of the East European Plain, in the continental part of the taiga zone. The region stretches from west to east by 600 km, from north to south, by 380 km. Forests dominate here, occupying about 75% of its area. The significant size of the region predetermines the diversity of natural environmental factors. The heterogeneity of the territory's topography causes redistribution of heat and moisture depending on the height, orientation, and steepness of the slopes. From west to east, the average annual temperature within the region decreases (from +2.5 to +1.5 °C), as well as the amount of precipitation does, when the difference in annual amounts reaches 160–170 mm (Priroda..., 2007).

The border between the western and eastern geomorphological regions is drawn along the western flank of the strip of lowlands adjacent to lakes Lacha, Vozhe, Kubenskoye and further across the Lezha River basin. In the western geomorphological region, the young, well-preserved glacial topography with various moraine ridges and hills and a relatively poorly developed river network preconditions the widespread appearance of lakes and favors swamp development. In the eastern geomorphological region, undulating and ridged moraine plains dominate along with a well-developed river network;

therefore, lakes and swamps are not widespread here (Kichigin, 2007). There are also some other differences between the western and eastern geomorphological regions: the degree of the lake content coefficient (up to 10% in the western region, < 0.2% in the eastern region) and the degree of swampiness of the territory (20–50% in the western region, < 1% in the eastern region).

The material was collected in five districts of the Vologda Oblast: Vytegorsky (1), Belozersk (2), and Cherepovets (3) districts, which belong to the western geomorphological region; and in Babushkinsky (4) and Nikolsky (5) districts of the eastern geomorphological region (Fig. 1). In each district, small mammals were captured in typical forest areas of the taiga zone.

Representatives of common species of small mammals were caught using Gero crushers filled with standard bait (bread fried in sunflower oil). A total of 252 ind. of common shrew (*Sorex araneus* L., 1758; order Eulipotyphla) and 220 ind. of common vole (*Microtus arvalis* Pallas, 1778; order Rodentia) were caught. The basis of the common shrew food spectra consists of small invertebrates: spiders, earthworms, and Coleoptera (Makarov and Ivanter, 2016). Common voles feed mainly on the food of plant origin (Vinogradov and Gromov, 1952). The body weight of the captured animals was measured, and the sex was determined. Samples of various organs and tissues (liver, kidneys, muscles, and brain) were placed in plastic bags, frozen and stored at a temperature of $-4...-16^{\circ}\text{C}$. Before analysis, organ samples were dried to constant weight at a temperature of 37°C .

The mercury content in organs and tissues was determined at the Regional Center for Collective Use of Cherepovets State University (Russia). The analysis was performed by pyrolysis on a PA-915 M atomic absorption spectrometer with a PIRO attachment (the minimum detection limit for mercury was $0.001\text{ }\mu\text{g/g}$). Assay accuracy was determined using certified biological material DORM-4 and DOLT-5 (Institute of Environmental Chemistry, Ottawa, Canada). Measurement accuracy was checked every 20 measurements (relative percentage difference (RPD) < 10%). The differences between replicates averaged 7.3%.

The obtained values of mercury content in organs did not follow a normal distribution (Shapiro–Wilk test); therefore, nonparametric methods were used in statistical analysis (Kruskal–Wallis U-test and Mann–Whitney H-test). Nonparametric Spearman correlation coefficient (r_s , $p < 0.05$) was applied to assess the relationships between the mercury content in different pairs of animal organs and the relationship between the mercury content in organs and total body weight of animal.

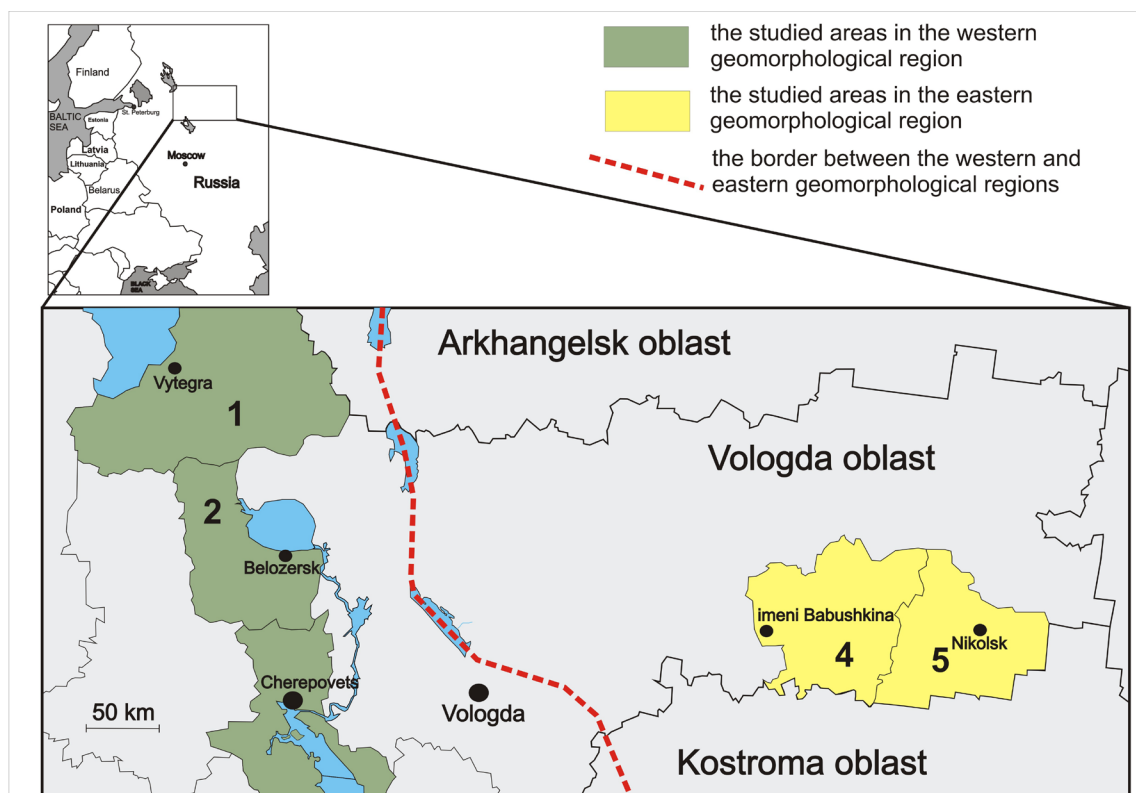


Fig. 1. Study areas.

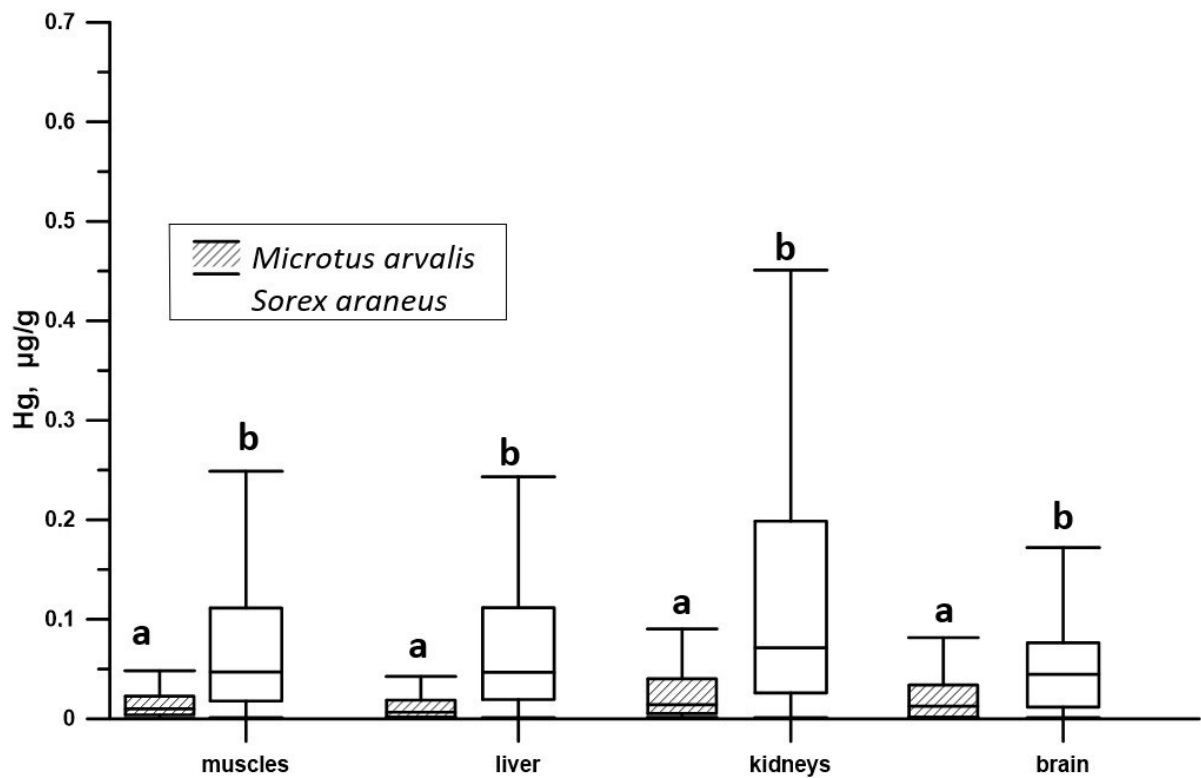


Fig. 2. Mercury content in the organs of small mammals, µg/g dry weight. Values with different letter indices are statistically different at a significance level of $p \leq 0.05$ (Kruskal–Wallis U-test).

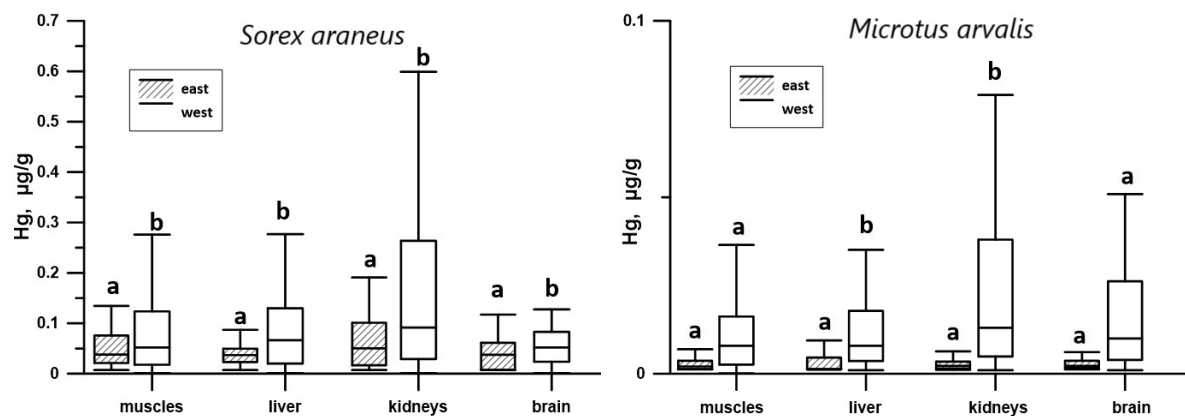


Fig. 3. Mercury content in the organs of small mammals from the eastern and western geomorphological parts of the Vologda Oblast, Russia.

Table 1. Mercury content in the organs of small mammals, µg/g dry weight. *N* – number of samples, mean – average values of the indicator, median – median, min and max – minimum and maximum values, Q25 and Q75 – lower (25%) and upper (75%) quartile, SD – standard deviation, SE – standard error of the mean. Values with different letter indices differ statistically significantly between organs for each individual species at a significance level of $p \leq 0.05$ (Kruskal–Wallis U-test).

Organ	n	mean	median	min	max	Q25	Q75	SD	SE	U-test
Common shrew										
muscles	179	0.084	0.047	0.001	1.467	0.0178	0.111	0.146	0.011	a
liver	194	0.086	0.047	0.001	1.674	0.0193	0.112	0.143	0.010	a
kidneys	202	0.158	0.071	0.001	1.764	0.026	0.199	0.222	0.016	b
brain	147	0.059	0.045	0.001	0.480	0.0118	0.076	0.073	0.006	a
Common vole										
muscles	154	0.016	0.007	0.000	0.355	0.0027	0.016	0.034	0.003	ab
liver	162	0.013	0.005	0.001	0.299	0.001	0.013	0.028	0.002	a
kidneys	191	0.026	0.010	0.001	0.359	0.0036	0.029	0.046	0.003	b
brain	137	0.024	0.009	0.001	0.325	0.001	0.024	0.044	0.004	ab

Table 2. Mercury content correlation in different pairs of organs of common shrew. Statistically significant correlations (Spearman coefficient; $p \leq 0.05$) are highlighted in bold; values above the line refer to the western geomorphological region ($n = 199$), below the line, to the eastern one ($n = 45$).

Organ	muscles	liver	kidneys	brain
muscles		0.71 0.65	0.81 0.64	0.39 0.48
liver	0.71 0.65		0.77 0.60	0.34 0.21
kidneys	0.81 0.64	0.77 0.60		0.39 0.33
brain	0.39 0.48	0.34 0.21	0.39 0.33	

Table 3. Mercury content correlation in different pairs of organs of common vole. Statistically significant correlations (Spearman coefficient; $p \leq 0.05$) are highlighted in bold; values above the line refer to the western geomorphological region ($n = 149$), below the line, to the eastern one ($n = 51$).

Organ	muscles	liver	почки	brain
muscles		0.59 0.06	0.47 0.16	0.26 –0.10
liver	0.59 0.06		0.67 0.52	0.27 0.14
kidneys	0.47 0.16	0.67 0.52		0.27 0.22
brain	0.26 –0.10	0.27 0.14	0.27 0.22	

Results

The mercury content in the organs of the studied mammals varied from trace values to 0.359 µg/g in common vole kidneys and even 1.764 µg/g in common shrew kidneys. Mercury content in all organs of common shrew was statistically significantly higher than that in common vole (Fig. 2). Mercury content in the brain of common shrew was 2 times higher than in the brain of common vole, while the Hg content in the muscles, liver and kidneys of Eulipotyphla representatives was 5–6 times higher on average than in Rodentia (Fig. 2).

In common shrew, mean content of total mercury (µg/g dry weight) decreases in the series: kidneys > liver > muscles > brain; in common vole, kidneys > brain > muscles > liver. Mercury content in kidneys of common shrew was statistically significantly higher compared to other organs. In common vole, statistically significant differences were noted only between the kidneys and liver. No statistically significant differences were found between other organs (Table 1).

When comparing mercury content in organs between males and females, no difference was found both for common shrew and for common vole (Mann–Whitney U-test, $p > 0.05$). No correlations were found between the Hg content in the organs and the animal body weight ($p > 0.05$).

Minimum mercury content has been noted both for common shrew and common vole captured in the eastern geomorphological region, the maximum content, for both species from the western region (Fig. 3). Mercury content in organs of ‘western’ common shrew was statistically significantly higher (2–3 times) for all organs studied. In ‘western’ common vole, the mercury content was statistically significantly higher (2 times) for organs with maximum HG content (liver and kidneys), although no differences were found for muscles and brain (Fig. 3, Table 1S).

In common shrew from the western region, there was a positive correlation between mercury contents in all pairs of organs ($r_s = 0.34–0.81$, $p < 0.05$). In the ‘eastern’ common shrew, the relationship between mercury content in organs was not noted only for the “liver-brain” pair (Table 2).

In the ‘western’ common vole, the mercury content between all organs correlated statistically significantly ($r_s = 0.34–0.81$, $p < 0.05$), except the “brain–any other organ” pairs. In ‘eastern’ common vole, a statistically significant correlation was noted only between the liver and kidneys ($r_s = 0.52$, $p < 0.05$) (Table 3).

Discussion

Average mercury contents in the organs of small mammals from the studied areas of the Vologda Oblast (0.013–0.158 µg/g) are comparable with the values noted in the organs of small mammals from the Voronezh Nature Reserve, non-industrial areas of Europe, and both Americas. At the same time, these values are several orders of magnitude lower than those of animals inhabiting the areas located near anthropogenic sources of Hg, e.g., thermal power plants, chlor-alkali production (Table 4). Regard must be also paid to the fact that when comparing mercury content measured in terms of dry and wet weight, the following values of water content in internal organs were used: 70.9% for the liver and 75.5% for the kidneys. Therefore, the wet-weight Hg content in the liver and kidneys may be estimated by multiplying the dry weight result by a factor of 0.3 and 0.25, respectively (Kalisinska et al., 2021).

The basis of the food spectrum of common shrew consists of animal food, primarily accessible and numerous groups of insects and earthworms. In addition, common shrew may consume spiders, mollusks, sometimes frogs, lizards, and even small mammals (Dolgov, 1985; Ivanter, 2008). Common shrew rarely consumes plant food in the study area. The seeds and vegetative organs of herbaceous and woody plants serve as the main food resource for common vole in all seasons of the year (Emelyanova, 2008). Small invertebrates (mollusks, insects and their larvae) are sometimes found in the food spectrum of common vole, but they do not play a large role in daily nutrition compared to plant food (Ivanter, 2008). It is well-known that the mercury content in the organs of first-order consumers is lower than in the species of higher trophic levels (Cristol et al., 2008; Komov et al., 2017; Kwon et al., 2015). This explains the fact that the mercury content in all studied organs of common shrew is statistically significantly higher than those in common vole.

Mercury ingested with food is unevenly distributed throughout the organs of animals. Both in common shrew and in common vole, Hg content in the kidneys is higher compared to other organs. Such results are consistent with earlier studies carried out within the taiga, forest-steppe, and steppe zones of the European part of Russia (Gremyachikh et al., 2019; Komov et al., 2017). It is likely that the mercury accumulation in the kidneys is due to the predominance of proteins with a high content of thiol, amine, carboxyl and hydroxyl functional groups, for which mercury has a high affinity (Clarkson and Magos,

Table 4. Mercury content in the organs of small mammals from different regions of the world; dw – dry weight, ww – wet weight.

Species	Region, degree of industrial development	Mercury content, µg/g	Reference
Order Rodentia			
<i>Apodemus flavicollis</i> (Melchior, 1834)	Poland, rural area	Liver: 0.007–0.015 ^{dw}	Durkalec et al., 2019
	Slovenia, territory of a lead smelting plant	Liver: 0.33 ^{ww}	Al Sayegh Petkovšek et al., 2014
<i>Apodemus uralensis</i> (Pallas, 1811)	UK, industrial area (< 0.05 km) chlor-alkali production	Muscle: 0.06–4.59 ^{ww} Liver: 0.09–0.53 ^{ww} Kidneys: 0.17–1.29 ^{ww} Brain: 0.09–1.88 ^{ww}	Bull et al. 1977
<i>Arvicola amphibious</i> (Linnaeus, 1758)	Russia, Karelia Republic, non-industrial area	Kidneys: 0.005 ± 0.002 ^{dw}	Ilyukha et al., 2019
	Poland, industrial area	Liver: 0.005–0.007 ^{ww}	Durkalec et al., 2019
	Slovenia, thermal power plant area	Liver: 0.32 ^{ww}	Al Sayegh Petkovšek et al., 2014
<i>Clethrionomys glareolus</i> (Schreber, 1780)	UK, industrial area (< 0.05 km) chlor-alkali production	Muscle: 0.08–0.66 ^{ww} Liver: 0.06–0.34 ^{ww} Kidneys: 0.14–0.75 ^{ww} Brain: 0.07–0.20 ^{ww}	Bull et al. 1977
	Russia, Voronezh State Reserve	Muscle: 0.007–0.02 ^{dw} Liver: 0.012–0.028 ^{dw} Kidneys: 0.012–0.094 ^{dw} Brain: 0.004–0.034 ^{dw}	Komov et al., 2010 Gremyachikh et al., 2019
		Liver: 0.04 ^{dw}	
<i>Melanomys caliginosus</i> (Tomes, 1860)	Colombia, natural park		Sierra-Marquez et al. 2018
<i>Nephelomys pectoralis</i> (J. A. Allen, 1912)		Liver: 0.12 ^{dw}	
<i>Peromyscus eremicus</i> (Baird, 1858)	USA, Nevada, bank of the Las Vegas Wash River (non-industrial area)	Liver: 0.001–0.09 ^{dw}	Gerstenberger et al., 2006
<i>Peromyscus maniculatus</i> (J. A. Wagner, 1845)	USA, Isle Royale Island, natural park	Liver: 0.035 ^{dw} Kidneys: 0.360 ^{dw}	Vucetich et al., 2001
<i>Rattus norvegicus</i> (Berkenhout, 1769)	USA, Georgia, mercury-polluted swamp	Muscles: 7.4 ^{dw} Liver: 15 ^{dw}	Gardner et al. 1978
<i>Sigmodon hispidus</i> (Say and Ord, 1825)		Muscle: 0.09 ^{dw} Liver: 3.8 ^{dw}	
<i>Thomasomys bombycinus</i> (Anthony, 1925)	Colombia, natural a park	Liver: 0.24 ^{dw}	Sierra-Marquez et al. 2018

Species	Region, degree of industrial development	Mercury content, µg/g	Reference
Order Eulipotyphla			
<i>Crocidura russula</i> (Hermann, 1780)	Portugal, remote area from industry	Liver: 0.1 ^{dw}	Marques et al. 2007
	Portugal, abandoned pyrite mine	Liver: 0.456 ^{ww} Kidneys: 0.119 ^{ww}	Sanchez-Cardi et al., 2007
	Portugal, Mor, area remote from industry	Liver: 0.418 ^{ww} Kidneys: 0.125 ^{ww}	
	Italy, province of Pesaro and Urbino, industrial area	Liver: 0.07 ^{ww}	Alleva et al., 2006
<i>Neomys fodiens</i> (Pennant, 1771)	Russia, Karelia Republic	Kidneys: 0.347±0.045 ^{dw}	Ilyukha et al., 2019
<i>Sorex araneus</i> (Linnaeus, 1758)	Russia, Cherepovets, industrial area	Muscle: 0.108 ^{dw} Liver: 0.124 ^{dw} Kidneys: 0.191 ^{dw} Brain: 0.065 ^{dw}	Komov et al. 2017
<i>Sorex cinereus</i> (Kerr, 1792)	USA, Minnesota, wetland	Muscle: 0.021 ^{dw} Liver: 0.012 ^{dw} Kidneys: 0.020 ^{dw} Brain: 0.007 ^{dw}	Tavshunsky et al. 2017

2006). Due to the formation of mercury conjugates with metallothioneins, glutathione, and a number of low- and high-molecular proteins, the kidneys are an important organ of deposition and detoxification. Blood filtration, neutralization, and removal of toxic substances from the body are carried out through kidneys. Previous studies have noted that the ratio of methylated and inorganic forms of mercury in different organs is not the same: in the brain and muscles, methylmercury accounts for 80–90% of the total mercury content, while in the kidneys and liver, the share of methylmercury does not exceed 40–55% (Strom, 2008). It is possible that in the liver, and especially in the kidneys of small mammals, a significant part of the total mercury is represented by inorganic compounds. The uneven content of mercury in the animal body may be associated with the heterogeneity of the distribution of inorganic and organomercury compounds in their habitat, the specificity of the accumulation of different forms of mercury by living organisms, as well as the peculiarities of the organ structure and functioning.

The mercury content in the organs of mammals from the western regions of the Vologda Oblast is higher than that from the eastern regions. This is due to the fact that the western and eastern regions differ in their natural and climatic characteristics. The western regions are characterized by the presence of a large number of lakes and wetlands, while the eastern regions have a high-density river network, but no large reservoirs or swamps (Priroda..., 2007). Earlier, it has been reported that increased mercury content in the organs of animals is predetermined by the presence of swamps and large stagnant bodies of water in their habitat areas, which may indicate the migration of mercury from aquatic ecosystems to terrestrial ones (Komov et al., 2012).

Unlike the western part of the Vologda Oblast, no correlations regarding mercury content have been found in different pairs of organs of animals from in the eastern regions. It is likely that the identification of statistically significant correlations between the Hg content in different pairs of organs occurs only at high mercury content.

Conclusions

Mercury content is statistically significantly higher (2–5 times) in organs of common shrew comparing to corresponding organs of common vole. The mercury content in the organs of small mammals from the western part of the Vologda Oblast, where there are many lakes and large areas occupied by swamps, is higher than in the animals inhabiting the eastern part with a developed river network. High correlation of the studied indicators, especially in common shrew from the western part, may indicate higher mercury levels in the study area and greater exposure of the studied species to the toxicant.

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APPENDIX

Table S1. Mercury content in the organs of small mammals in various geomorphological regions, µg/g dry weight: n – number of samples, mean – average values of the indicator, median – median, min and max – minimum and maximum values, Q25 and Q75 – lower (25%) and upper (75%) quartile, SD – standard deviation, SE – standard error of the mean. Values with different letter indices differ statistically significantly between organs for each individual species at a significance level of $p \leq 0.05$ (Mann–Whitney U-test).

Region	n	mean	median	min	max	Q25	Q75	SD	SE	U-test
Order Eulipotyphla										
Common shrew <i>Sorex araneus</i>										
Muscles										
West	131	0.098	0.052	0.001	1.467	0.018	0.124	0.167	0.015	b
East	48	0.045	0.032	0.001	0.173	0.014	0.067	0.043	0.006	a
Liver										
West	141	0.104	0.066	0.001	1.674	0.020	0.130	0.163	0.014	b
East	53	0.039	0.031	0.001	0.207	0.017	0.044	0.038	0.005	a
Kidneys										
West	149	0.187	0.092	0.001	1.764	0.029	0.264	0.245	0.020	b
East	53	0.075	0.044	0.001	0.616	0.011	0.095	0.106	0.015	a
Brain										
West	101	0.068	0.052	0.001	0.480	0.024	0.083	0.082	0.008	b
East	46	0.038	0.031	0.001	0.171	0.001	0.055	0.042	0.006	a
Order Rodentia										
Common vole <i>Microtus arvalis</i>										
Muscles										
West	105	0.017	0.008	0.001	0.355	0.003	0.016	0.039	0.004	a
East	49	0.014	0.005	0.001	0.084	0.003	0.015	0.020	0.003	a
Liver										
West	95	0.018	0.008	0.001	0.299	0.004	0.018	0.034	0.004	b
East	67	0.007	0.001	0.001	0.084	0.001	0.005	0.014	0.002	a
Kidneys										
West	121	0.032	0.013	0.001	0.359	0.005	0.038	0.051	0.005	b
East	70	0.016	0.007	0.001	0.267	0.002	0.018	0.034	0.004	a
Brain										
West	67	0.026	0.010	0.001	0.141	0.004	0.026	0.027	0.003	a
East	70	0.022	0.001	0.001	0.048	0.001	0.024	0.056	0.007	a